

Assessing Loading Regimes and Failure Modes of Marine Power Cables in Marine Energy Applications

Philipp R. Thies¹, Lars Johanning¹, George H. Smith¹

¹CEMPS – College of Engineering, Mathematics and Physical Science
Renewable energy research group, University of Exeter
Cornwall Campus, Treliever Rd, Penryn, TR10 9EZ, UK
E-mail: prt203@exeter.ac.uk

Abstract

Highly reliable marine power cables are imperative for the cost-effective operation of marine energy conversion systems. Cable manufacturers and installers have considerable experience with marine power cables when deployed to operate under static or dynamic load conditions, but highly dynamical power cables for marine renewable energy converters have large uncertainties.

The mechanical loadings of a power cable attached to a floating marine energy converter will be considerably different to the present applications like remotely operated vehicles (ROVs) or oil and gas umbilicals. The floating structure responds to the wave action and transfers this dynamic motion to the attached power cable. Moreover the frequency of response will be at the wave period (linear case) leading to considerable cyclic effects. At present the loading regime in such applications is not well understood, due to a lack of field experience.

The paper describes the parameters and results of a dynamic computational model that investigates the umbilical load conditions for a generic wave energy converter. Two geometric configurations of a double armoured power cable are considered, a catenary and a Lazy Wave shape. The model is set up using the dynamic analysis package OrcaFlex and uses top-end motions measured in 1:20 wave tank tests.

While the simple catenary shape experiences high tensional forces at the attachment point and considerable compression, the maximum tensional forces can be significantly reduced and compression is avoided with a Lazy Wave shape. For this configuration the highest tension occurs near the attachment point and at the transition points of the buoyancy section.

For the modelled conditions, the power cable accumulated a significant number of tension and bending load cycles, indicating that power cables in floating marine energy applications will operate in a high cycle regime (in the order of 10^6 cycles) likely to accumulate several million load cycles during a single year of operation.

1. Introduction

Electricity transmission across the sea via subsea power cables has been undertaken by engineers for more than a century and is a well established

technology [1]. The large majority of the current applications are static, i.e. the cable is connected to a fixed structure like a pile or foundation and is not subject to significant cyclic loading. Furthermore power cables have been used in dynamic applications (floating oil and gas platforms, ROVs). A dynamic power cable has to withstand considerable cyclic loads induced by the moving floating body, the waves and the currents.

The objective of this paper is to assess the potential failure modes and mechanical loads of a typical subsea power cable in the application of a floating wave energy converter, which could be considered *highly* dynamic. This is part of the ongoing and future work undertaken within the research group at the University of Exeter to assess the reliability of marine renewable energy components. The general approach towards component testing and the associated test facilities to measure and replicate the dynamic load conditions for floating marine energy devices are described in [2-4].

The paper is organised in five main parts. It briefly describes the design of marine power cables, potential failure modes (section 2) and how the dynamic behaviour of can be modelled (section 3). Section 4 presents the experimental tank tests carried out for the wave device and the associated computational model. Section 5 presents and discusses the results for two cable geometries, a catenary and a Lazy Wave configuration. The paper concludes with the key findings and briefly touches on further work to allow a complete fatigue assessment.

2. Marine power cables

2.1 Design

There is a multitude of different designs and configurations of submarine power cables, but a typical marine power cable comprises of seven layers (comp. e.g. [1], see Figure 1 for an example):

1. *Conductor core*: The cable core carries the electrical current and consists of further wires, made out of either copper or aluminium.
2. *Electrical insulation*: The electrical insulation can be achieved by three different design/material types:
 - a. Traditional method of oil impregnated paper.
 - b. Cross-linked polyethylene (XLPE)
 - c. Ethylene propylene rubber (EPR)
3. *Screen*: A semi-conducting conducting layer of paper/extruded polymer around the core in order to minimise electric field strength and avoid field concentration zones.
4. *Sheath*: Around the core a metallic sheath is applied as water barrier and to protect the cable against fault currents.
5. *Armature*: The entire cable is surrounded with metallic armature to provide necessary mechanical strength and impact protection for the cable.
6. *Optic fibre*: Numerous fibre optic cables may be used for data transmission and monitoring purposes.

7. *Protecting sheath*: The outer layer consists of polypropylene for abrasion resistance

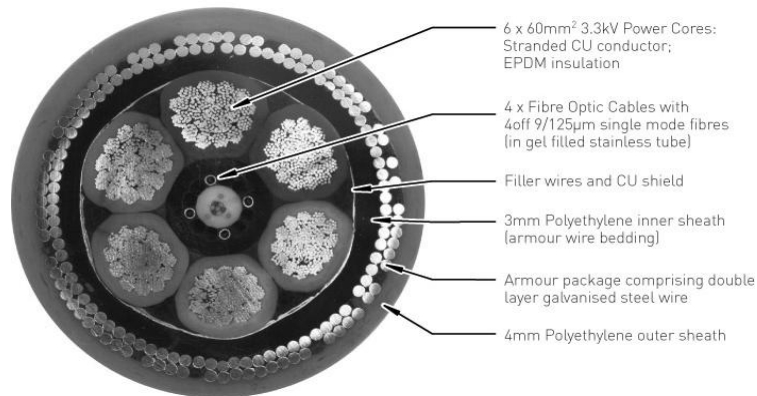


Figure 1. Example of HVAC (3.3kV) subsea power umbilical (courtesy of JDR [5])

The multitude of materials and configurations used results in complex mechanical behaviour of marine cables under load and difficulties to predict the service life with confidence. It is further important to note, that there is no standardised marine cable and that manufactures usually tailor-make submarine cables to the application at hand. Hence the listed cable layers are combined in cylindrical and/or helical configuration with varying diameters and differing cross-sectional designs.

To attach the power cables to floating marine structures, different lay configurations are possible to lead the cable across the water column. Some standard configurations are shown in Figure 2. The two configurations that are investigated in this paper are the simple free hanging (so-called catenary) shape and the Lazy Wave shape where the cable is supported with buoyancy floats to create a long radius curve.

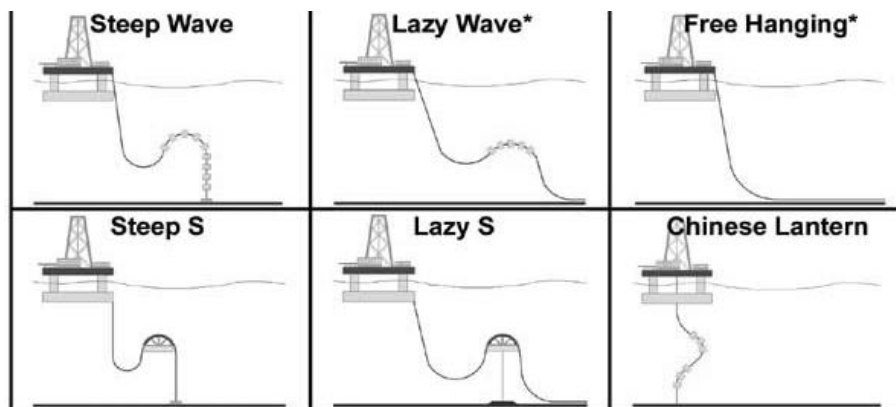


Figure 2. Standard flexible riser configurations for floating offshore structures [6]

2.2 Reliability and failure modes

There are many failure modes for marine cables and umbilicals ranging from material degradation to fatigue failure which makes life predictions difficult, as

not all critical failure modes may be covered [7]. This is particularly the case for harsh and dynamic environments like floating wave energy converters where the loading conditions are not well understood. In the following a summary of available reliability information and failure modes from the literature is presented.

The Umbilical Manufacturers' Federation (UMF) [8] has reported failures of control umbilicals for a 5 year period (1995 - 2000). Failure was defined as an incident that is detrimental to the functionality of the fluid conduits, electrical conductor or fibre optical cable. The umbilicals in this study were mainly of the electro-hydraulic type. A total of 21 incidents were reported, with the majority of 17 failures during installation and commissioning and almost half the failures associated to manufacturing and installation errors. Most mechanical failures were associated to the failure of attachment/hang-off points.

Patel [9] summarises the outcomes of a reliability study for electrical cables in umbilicals. The study comprised a total of 62 failures, where almost 50% of the failures are ascribed to incorrect installation and loadout, followed by electrical faults, incorrect operation or design flaws. Other named failure causes were fatigue failures, poor manufacturing, marine life (marine growth, shark attacks) and accidents.

As this highlights the importance of careful installation of umbilicals, it also emphasises the fact that mechanical failures do occur if not all load parameters are considered in the design process

Mechanical failure modes	Applicability to marine energy converters
Severe axial tension or torque	Likely for motion dependent devices
Over bending	Likely at attachment points and buoyancy intersection
Crushing due to extreme external pressure	Not likely due to moderate water depth
Hose/tube bursting by excessive internal pressure	Not applicable for pure power cables
Layer separation and instability	Possible
'Birdcaging' caused by sudden tension release, spreading wire strands	Possible if umbilical under compression (e.g. at the touchdown point)
Loop formation and kinking	Possible
Mechanical degradation (wear and fatigue)	Can be expected for motion dependent devices

Table 1: Mechanical failure modes of umbilicals [9] and applicability to marine energy converters

Table 1 lists a number of mechanical failure modes for marine power cables and tries to assess the applicability for MEC applications. Three mechanical failure modes are likely to be of concern for floating wave energy converters and will be further assessed in the following:

- Exceedance of axial tension limits,
- Overbending of the umbilical,
- Degradation under extreme dynamic and cyclic loading.

These are most likely to appear at the top-end and at transition points.

The methodology applied in this paper follows a physical reliability approach, aiming to assess and replicate realistic component load conditions to provide evidence of component reliability under operational conditions. The process can be divided into four successive steps [4]:

1. Measuring realistic load data,
2. Identifying representative loading regimes,
3. Testing component under representative loads,
4. Root cause analysis and statistical evaluation of test results.

This paper is concerned with the first two steps. To establish the realistic load, experimentally measured motions are used as input for a computational load model. The loading regime is then assessed for different cable configurations. The results can be used to inform the design and testing of marine dynamic power cables.

3. Modelling of marine cable dynamics

Worzyk [1] presents a simplified approach to estimate the maximum occurring tensional forces during the cable laying process (see Equation 1). The maximal top tension force F_{\max} is estimated as the sum of the static tensional Force F_S (due to the cable weight) and the dynamic Force F_D (due to the wave elevation). The maximum vertical acceleration b_{\max} is estimated for a sinusoidal heaving motion.

$$\begin{aligned}
 F_{\max} &= F_S + F_D \\
 F_{\max} &= w \cdot D + m \cdot b_{\max} \\
 F_{\max} &= w \cdot D + m \cdot \frac{1}{2} h \cdot \left(\frac{2\pi}{T} \right)^2
 \end{aligned}
 \tag{1}$$

Where w = unit weight of cable in water; D = water depth; m = mass of cable; h = heave amplitude; T = movement period; b_{\max} = maximum vertical acceleration

While the static force is governed by the unit weight in water, the dynamic force is due to inertia and therefore requires the mass of the cable. Although this equation gives an indication of the maximum tension forces the assumption of sinusoidal movements does not always hold. The wave elevation of real waves does not follow a sinusoidal motion and has steeper wave fronts. In such cases the resulting forces will be significantly larger than calculated with Equation 1.

For this paper the proprietary marine dynamics software OrcaFlex[®] from Orcina has been used to estimate the loadings of the umbilical. The software is a three-dimensional non-linear time domain finite element program which employs a lumped mass element approach to solve the dynamic behaviour of line objects [10]. The 3D mass-spring-damper system is illustrated in Figure 3.

The complex computational method allows the estimation of realistic loads under fully dynamic conditions, i.e. going beyond the simplified sinusoidal estimation. To achieve this however, the input parameters for the simulation have to be highly accurate.

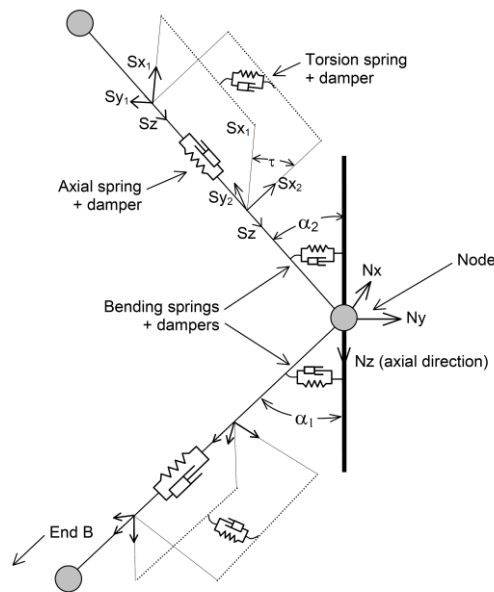


Figure 3. Mass-spring-damper line model (taken from [10])

4. Experimental tank tests and umbilical modelling

Ideally, load data for umbilicals is of course measured in the field. However, actual field experience is scarce and initial umbilical load estimates for floating marine energy devices are often based on tank tests and/or computational modelling [11].

In this paper a combined approach is presented, where experimentally measured top-end motion responses are applied in a numerical model, to assess the top-end tension and bending characteristics of a marine power cable.

4.1 Experimental tests

The experimental tank tests were conducted at the MARINTEK institute in Trondheim, Norway and had the objective to study the interaction of floating wave energy devices installed in arrays for a number of operational sea states. The devices are at 1/20 scale and are of the Oscillating Water Column type (OWC). The operating principle for this kind of device relies on the wave motion that displaces air in a chamber open below the water surface. The alternating airflow can then be used to drive a turbine (see e.g. [12] for a more detailed description). Figure 4 shows the experimental setup and mooring dimensions of the device which was instrumented with mooring line load cells, optical motion trackers and accelerometers. Different wave conditions were applied to the device while device motion and mooring forces were monitored [13]. No power cable was attached during these experiments.

Each wave climate was run for 30min, with a high sample frequency $f = 20\text{Hz}$ to enable the measurement of highly dynamic loads. All data shown in the following has been upscaled using Froude's scaling law [14].

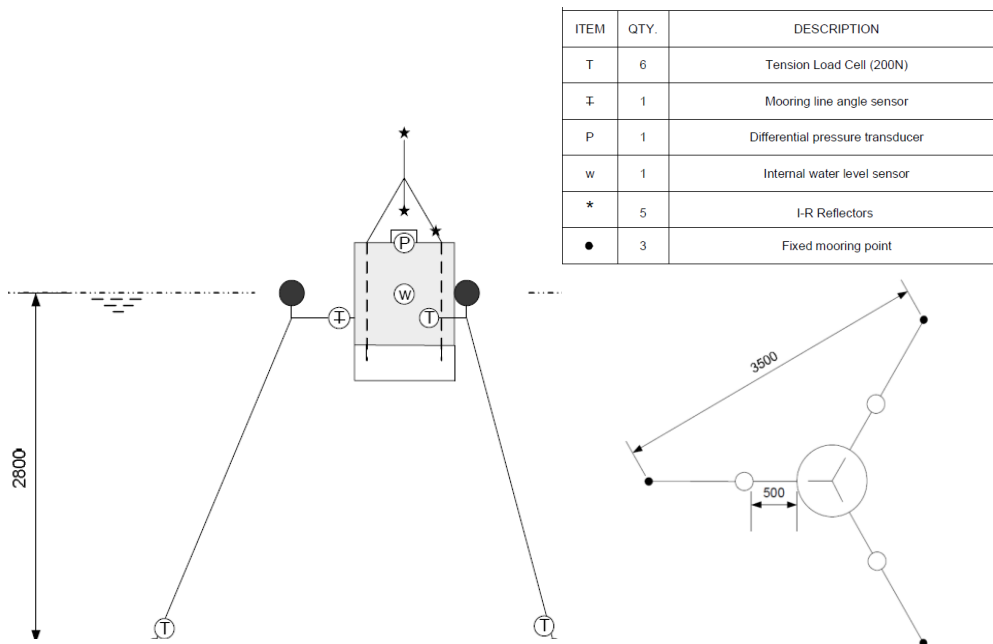


Figure 4. Experimental setup and mooring dimensions [mm] of generic floating OWC used in HydralabIII test. Left – elevated view; Right – instrumentation and plan view.

Figure 5 shows a 30second excerpt of the data recorded for irregular waves with significant wave height $H_s = 3.5\text{m}$ and wave period $T = 8.0\text{s}$. The translational and rotational response for every motion axis is depicted against the measured wave elevation. The vertical displacement (heave) and rotation of the x-axis (pitch) constitute the main movements of the device, which is expected, as the device approximately follows the wave elevation and the x-axis was defined perpendicular to the incoming wavefront.

The measured motions in all 6 degrees of freedom are being used to inform the computational model described in the following section (4.2). The motions are superimposed on a floating body that has a power cable connected to it. Hence the assumption made for the model is that the umbilical itself does not significantly alter the motion of the floating device.

4.2 Computational model

In order to estimate the loads for a typical dynamic power cable attached to a wave energy converter, a model in Orcaflex [10] has been set up, comprising of the following elements:

- Floating wave energy device with six degrees of freedom
- Power cable
- Attachment point at the bottom centre floating device, modelled as flexible joint
- Anchor point on the seabed

The power cable has been modelled as double armoured cable in two geometric configurations i) catenary and ii) Lazy Wave (see Figure 6).

In order to achieve the Lazy Wave shape additional floats have been covered around the cable. The double armour configuration provides the tension stability and mechanical protection. The total cable length is 120m (catenary) and 130m (Lazy Wave) in a water depth of 57m. The properties of the umbilical and the buoyancy section are given in Table 2.

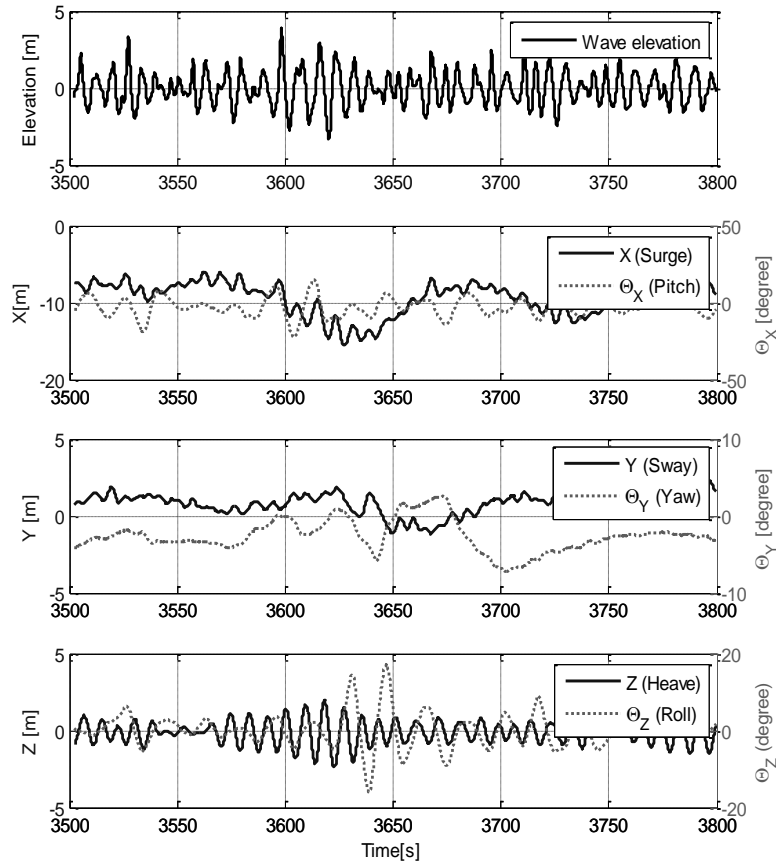


Figure 5. Sample section for six degree of freedom motion response of wave device ($H_s = 3.5\text{m}$, $T = 8\text{s}$).

Top - wave elevation. Three lower plots show translational and rotational displacements for each motion axis. Left ordinate - translational movements (X, Y, Z); Right ordinate – Rotational movements (θ_X , θ_Y , θ_Z);

For the simulation, the motions measured in the wave tank are imposed on the floating body for all six degrees of freedom. The integration time step was set to 0.02s, which is sufficiently small to capture high frequency responses.

Name	Unit	2-Armoured cable	Buoyancy section
Total length	m	50 (section 1) 30 (section 3)	40 (section 2)
Outside diameter	mm	200	306
Nominal weight in air	N/m	706	423
Nominal weight in seawater	N/m	390	-316
Bending stiffness	kN.m ²	10	10
Axial stiffness	MN	700	700
Torsional stiffness	kN.m ² /deg	600	600

Minimum Breaking Load	kN	100	100
Minimum bend radius (MBR)	m	2	2
Connection stiffness	kN.m/deg	X-bend: 10 y-bend: stiff	X-bend: 10 y-bend: stiff

Table 2: Characterisation data for modelled umbilical (armoured cable properties after [11]; connection stiffness [15])

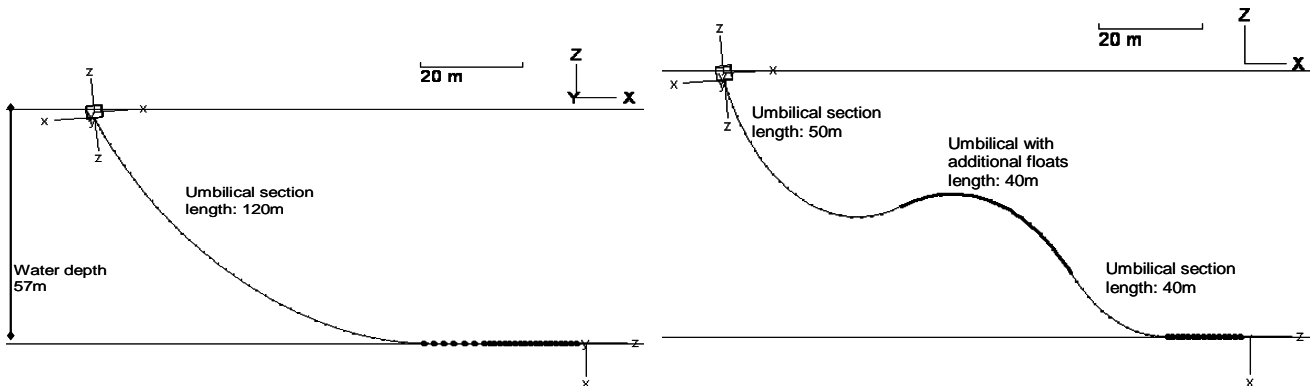


Figure 6: Orcaflex model of armoured power cable in catenary (left) and Lazy Wave configuration (right) attached to a buoy with 6 degrees of freedom

5 Discussion of results

5.1 Comparison of sinusoidal approximation and dynamic computation

The maximum tensional force at the hang-off point is estimated with Equation 1, assuming pure sinusoidal motions of the top-end [1]. This is done for both configurations the simple catenary-, and the Lazy Wave shape. Table 3 compares the results with the maximum tensions computed in the dynamic simulation.

Max. tensional forces [kN]	Power cable configuration	
	Lazy-Wave	Catenary
Sinusoidal approximation	26.5	32.6
Dynamic simulation	21.4	102.0

Table 3: Comparison of maximum tensional forces [kN] at power cable hang-off point for different geometric configurations and calculation methods.

The highest tensional force in case of the Lazy Wave shape is $F_{max, sim, Lazy} = 21.4 kN$ which is below the maximum force estimated with the sinusoidal approximation. The opposite is the case for the catenary configuration. The approximation estimate is 32.6 kN while the simulation yielded a maximal tensional force $F_{max, sim, Catenary} = 102 kN$.

The disparate findings for Lazy Wave / catenary highlight the uncertainty of peak tension in dynamic applications, in particular for the catenary

configuration. While the sinusoidal approximation is in reasonable agreement with the simulation results for the Lazy-Wave, the approximation does considerably under predict the max. tension force for the catenary shape, i.e. the sinusoidal assumption does not hold.

Moreover, the sinusoidal approximation does not provide any load information along the length of the cable, so for this reason a dynamic simulation is carried out, which computes the forces and moments for every node along the line object and hence allows assessing the load conditions along the cable.

5.2 Dynamic computational results

The range graph in Figure 7 shows the maximum, mean and minimum tension forces along the entire power cable for both configurations. The catenary shape exceeds the allowable tension at the attachment point and experiences compression loads, in particular at the touchdown point. For the catenary configuration the hang-off point is the area of highest tension.

In case of the Lazy Wave, the highest forces occur near the attachment point and at the transition points of the buoyancy section. Forces are reduced and compression is avoided in comparison to the catenary but at the price of two load peaks at the transition points of the buoyancy section. This is consistent with the guidelines given in [16] which identify the area in the wave zone, hog- and sag bends and terminations as the most critical, failure-prone locations. In the following the focus will be on the load conditions near the attachment point.

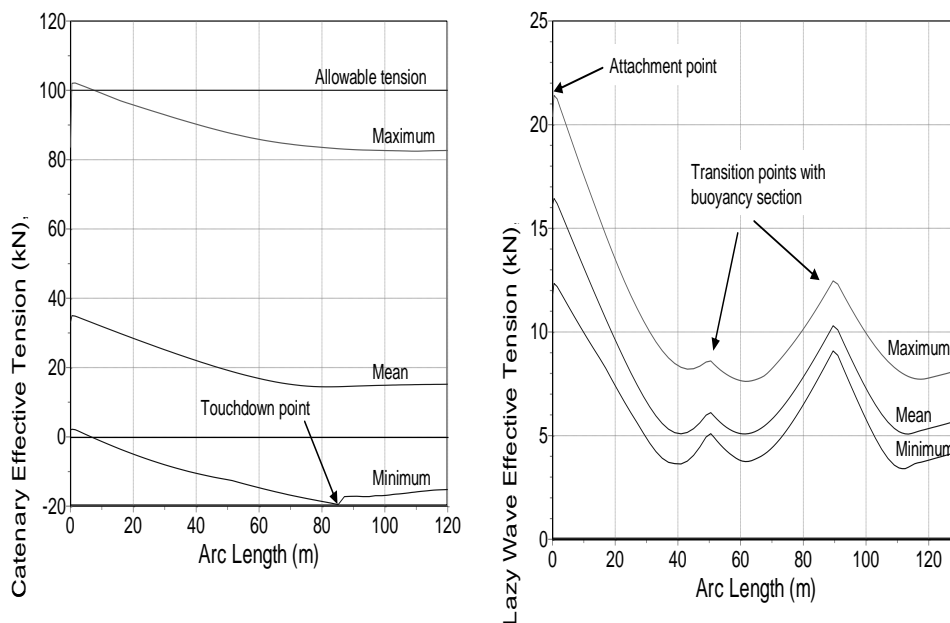


Figure 7: Minimum, mean and maximum effective tension along the length of the power cable. Left – catenary; right - Lazy Wave configuration. Negative values indicate compression.

5.2.1 Tensional forces near attachment point

Figure 8 shows the time series of the simulated forces near the attachment point. It can be seen how the Lazy Wave configuration reduces the maximum

force in comparison with the catenary shape, over the same time period and with the same motions of the floater.

Furthermore, Figure 8 illustrates the oscillatory, cyclic nature of the tensional forces. Indeed, for the test period of 135 minutes, more than 1,500 load cycles occur (3,124 half cycles). If these cycles are projected for a year worth of operation in such conditions, the umbilical would have to withstand a total of $5.84 \cdot 10^6$ load cycles. To put this into context, the number of load cycles railway axles and wheels typically experience over their service time, is a multiple of 10^6 – 10^7 cycles [17].

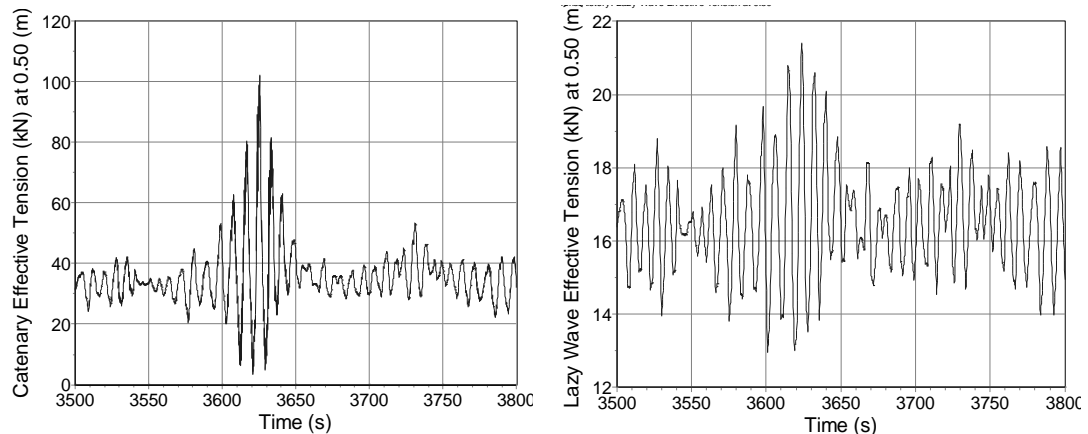


Figure 8: Time series of the effective tension 0.5m off the attachment point. Left – catenary; right - Lazy Wave configuration. *N.B. different scales of y-axis*

5.2.2 Bend Moment and minimum bend radius near attachment point

The resulting bending moment near the attachment point is depicted in Figure 9. The largest moments are just under 6kN (catenary) and 4kN (Lazy Wave). The bending moment correlates to a bending radius of the umbilical which is typically used as design parameter.

For the modelled cable the minimum bend radius is given as $MBR=2m$, i.e. the bend radius must not be smaller in order not to damage the cable. The calculated bend radius is shown in Figure 10. It can be seen, that for the largest bend moments, the bending radius exceeds the critical value of 2m for the catenary and comes close for the Lazy Wave shape.

Bending radii close to or beyond the minimum bending radius are an indication, that an additional bend stiffener may be required to restrict the bending and avoid kinking and cable damage.

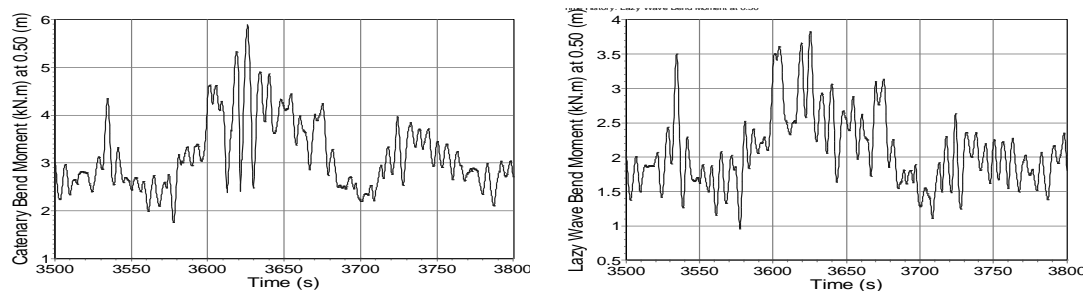


Figure 9: Bending moment time series at 0.5m off the attachment point. Left - catenary; right - Lazy Wave configuration

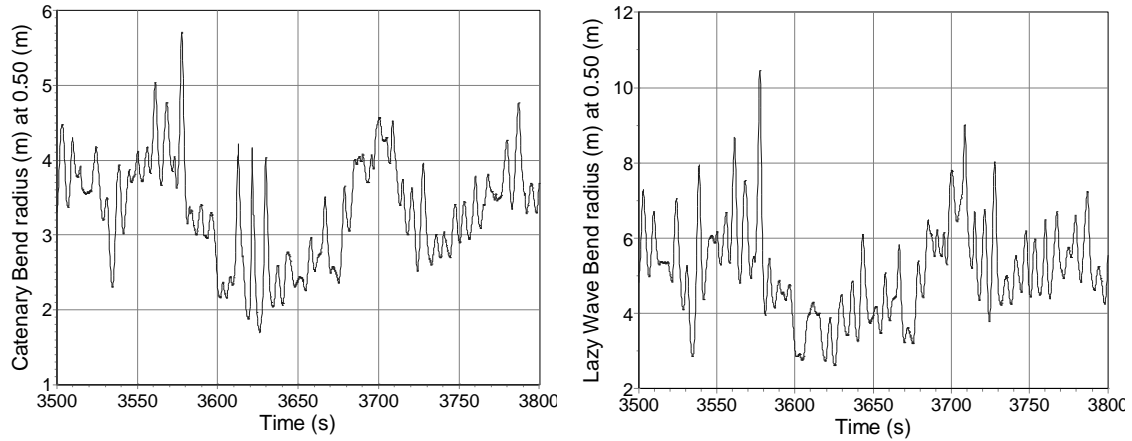


Figure 10: Bending radius moment time series at 0.5m off the attachment point. Left - catenary; right - Lazy Wave configuration

5.2.3 Cyclic loading near attachment point

To evaluate the fatigue damage of load signals with randomly varying load amplitudes, the so-called rainflow count method is commonly applied. The rainflow cycle algorithm identifies and counts the stress range corresponding to individual hysteresis loops [18].

A comparison of the counted rainflow halfcycles regarding motion response and load cycles (Table 4) shows, that the load cycles are more numerous than it would be expected from solely considering any single degree of freedom. This is the case for both tensional forces and bending moments.

The cumulative distribution plots of rainflow cycles for both tensional forces and bending moments of the Lazy Wave configuration are shown in Figure 11. About 50% of tension cycles have a range larger than 2kN, corresponding to about 780 full load cycles in 135min and $3 \cdot 10^6$ cycles for an entire year under the simulated conditions. Regarding the bend moment cycles, more than 40% are larger than 0.5kN.m. This means 530 full bend cycles at this stress range and an estimated $2 \cdot 10^6$ cycles for an entire year.

Motion response of device		Loading (0.5m off attachment point)		
		Configuration	<i>Catenary</i>	<i>Lazy-Wave</i>
Surge (X)	2,214	Tension cycles	3,846	3,124
Sway (Y)	2,275		Bend moment cycles	3,603
Heave (Z)	1,856			
Pitch (θ_x)	1,198			
Yaw (θ_y)	1,480			
Roll (θ_z)	1,262			

Table 4: Rainflow halfcycles for motion response of the device and loading near attachment point for different umbilical configurations, for the length of the simulation (135min).

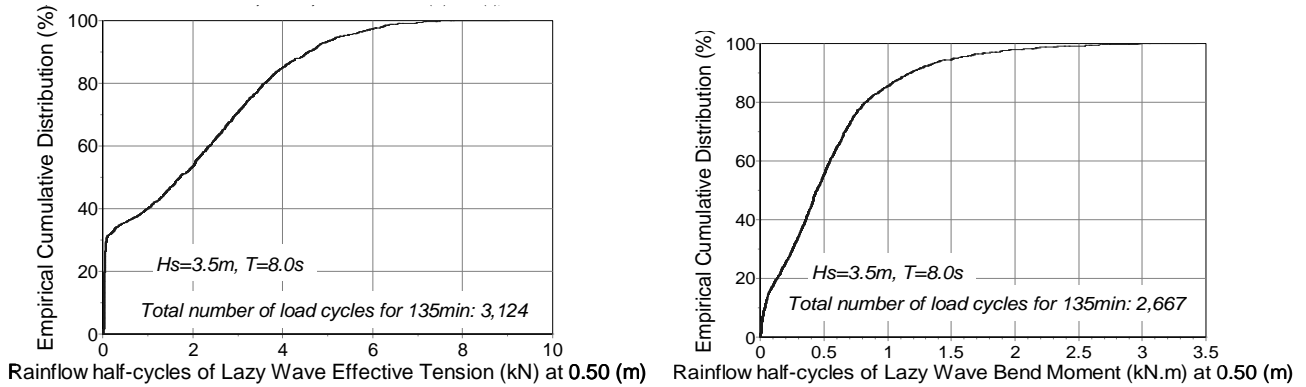


Figure 11: Empirical cumulative distribution of rainflow half-cycles for Lazy Wave umbilical (0.5m off attachment point). Left – effective tension; right – Bend moment.

6. Conclusion and further work

For the modelled highly dynamic application the compliance of the lazy wave umbilical configuration clearly reduces the tension at the hang-off point and the compression at the touchdown point compared to a catenary system. The motions of the floating body determine the maximum tension and moments making the area of the attachment point and the hog-and sag bends the most critical, failure-prone locations.

The comparison of sinusoidal approximation and simulation results has shown that the maximal tensional forces for the Lazy Wave configuration is similar, while for the catenary shape the approximation under predicts the maximum force and a variation of factor 3 was identified. However, load conditions along the umbilical need to be assessed with a dynamic computational model.

The mechanical loading regime (tension and bending) of the power cable was shown to be highly cyclic. The simulation for an irregular seastate indicates, that several million load cycles might be accumulated within only one year of operation. This highlights the importance to consider possible fatigue failures in the design and testing of dynamic power cables for floating marine energy applications. The simulation has further shown that the number of load cycles can not be simply estimated by considering a single degree of freedom. The load cycles are a result of the combined motions in six degrees of freedom and are more numerous than would be expected from a single degree of motion.

Further work and analysis is needed for a complete fatigue assessment, where the cyclic load conditions for a typical year of operation in the site-dependent sea-states are considered. Furthermore real measurements from realistic sea trials would enhance this work by providing realistic forces and load cycles. This is part of ongoing work within the research group [4].

Similarly, the top-end motions measured during the tank tests are currently used to assess the mechanical load conditions of the umbilical in more extreme sea states up to 6m significant wave height.

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